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Reliability design optimization of composite structures based on PSO together with FEA

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Abstract The present work aims to develop a method for reliability-based optimum design of composite structures. A procedure combining particle swarm optimization (PSO) and finite element analysis (FEA) has been proposed. Numerical examples for the reliability design optimization (RDO) of a laminate and a composite cylindrical shell are worked out to demonstrate the effectiveness of the method. Then a design for composite pressure vessels is studied. The advantages and necessity of RDO over the conventional equi-strength design are addressed. Examples show that the proposed method has good stability and is efficient in dealing with the probabilistic optimal design of composite structures. It may serve as an effective tool to optimize other complicated structures with uncertainties.

1. Introduction

Composite materials have been widely applied in construction of components in mechanical, aerospace, shipbuilding, and other industries. Since these composite structures are generally in service under special and severe circumstances, where lots of unavoidable uncertainties exist, it is necessary to take the uncertainties into consideration when designing these structures. In order to accommodate and manage the effects of uncertainties on design performance, a number of methods such as reliability design optimization (RDO), safety analysis, robust based design, and system identification have been developed.[1–4] The objective of RDO is to seek a design that achieves a targeted probability of failure and ensures expected optimum performance.[5]

In structural reliability analysis, reliability is defined as a multidimensional nonlinear integral. Direct evaluation of such an integral is unfeasible or even impossible in most cases. Therefore, some approximation or simulation methods for probabilistic uncertainty analysis[6–8] have been developed, among which most probable point (MPP) based methods are widely used in RDO since they have the advantages of satisfactory accuracy and moderate computational cost.[9–11] Typical MPP-based methods include the first order reliability method (FORM), the second order reliability method, and the first order saddle point approximation.

A qualified reliability design optimization of composite structures directly depends on two aspects[12,13]: (i) an optimization technique that can efficiently find the global solution; (ii) a

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structural analysis tool that can accurately evaluate the stresses of complicated composite structures.

Conventional optimization algorithms are computationally efficient in general, but often encounter a problem that the optimum results are sensitive to the initial condition and differentiation calculations are required. In order to overcome the shortcomings of these algorithms, several biologically inspired evolutionary algorithms[14–18] have been developed. They differ from the most traditional optimization techniques in that they involve a search from a "population" of candidate solutions, not from a single point. As compared with other evolutionary methods, particle swarm optimization (PSO) has no complicated evolutionary operators such as crossover, selection, and mutation. Information in the search procedure of PSO is socially shared among individuals to direct the search towards the best position in the search space.[18] For numerically analyzing composite structures, on the other hand, the commercial FEA code ANSYS[19] provides diversiform element types which can be chosen according to the specific applications of composite structures.

Several researchers have adopted PSO or improved PSO to carry out optimal design of composite structures.[20–25] A technique of applying PSO integrated with general finite element code was developed by Peng et al. to minimize interlaminar normal stresses at the free-edge.[24] Ge et al.[25] proposed an improved PSO algorithm and applied it to RDO of composite materials. However, classic lamination theory was used to obtain stresses. Up to now, few works have been reported in literature about the use of evolution algorithms (EAs) together with FEA for RDO of composite structures.

In this paper, a design procedure for RDO is proposed which is based on PSO together with the FEA code ANSYS. The approach includes three modules: (1) stress analysis by ANSYS; (2) reliability calculation; and (3) optimization. Numerical examples for reliability-based optimum design of laminates, composite cylindrical shells, and composite pressure vessels are worked out to demonstrate the effectiveness of the proposed method.

2. Reliability analysis for composites and reliability based design procedure

2.1. Tsai–Wu failure criterion

Tsai–Wu failure criterion[26] is the most reasonable failure criterion for composites. It can be expressed as

$$FI = F_1\sigma_1 + F_2\sigma_2 + F_3\sigma_3 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{33}\sigma_3^2 + 2F_{12}\sigma_1\sigma_2 + 2F_{23}\sigma_2\sigma_3 + 2F_{31}\sigma_3\sigma_1 + F_{44}\sigma_4^2 + F_{55}\sigma_5^2 + F_{66}\sigma_6^2 \leqslant 1 \quad (1)$$

where

$$F_1 = 1/X_T - 1/X_C, \quad F_2 = 1/Y_T - 1/Y_C,$$
$$F_3 = 1/Z_T - 1/Z_C$$

$$F_{11} = 1/(X_T X_C), \quad F_{22} = 1/(Y_T Y_C), \quad F_{33} = 1/(Z_T Z_C),$$
$$F_{44} = 1/S_{yz}^2, \quad F_{55} = 1/S_{zx}^2, \quad F_{66} = 1/S_{xy}^2$$

$$F_{12} = (-1/2)\sqrt{F_{11}F_{22}}, \quad F_{23} = (-1/2)\sqrt{F_{22}F_{33}},$$
$$F_{31} = (-1/2)\sqrt{F_{33}F_{11}}$$

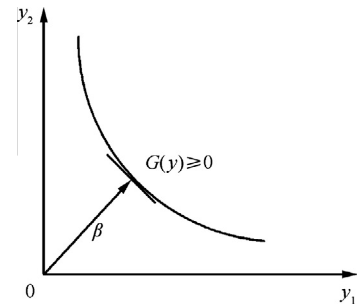

Fig. 1 Geometrical illustration of the reliability index β.

where X_T and X_C are tensile and compressive strength in the longitudinal direction, respectively; Y_T, Z_T, Y_C and Z_C are tensile and compressive strength in the transversely isotropic surface, respectively; S_{xy}, S_{yz} and S_{zx} are shear strength in the transversely isotropic surface. Therefore, the limit state function in terms of Tsai–Wu failure criterion can be expressed

$$G = 1 - FI \quad (2)$$

The composite element is in operating state if $G > 0$, in failure state if $G < 0$, and in limit state if $G = 0$.

2.2. Reliability analysis

In the structural reliability analysis, the reliability is defined as

$$R_s = \mathrm{P}[g(\boldsymbol{d}, \boldsymbol{X}) \geqslant 0] = \int_{g(\boldsymbol{d},x)\geqslant 0} f_X(x)\mathrm{d}x \quad (3)$$

where g is a performance function or the limit state function, $\boldsymbol{d}$ a vector consisted of the design variables, and f_X the joint probability density function (PDF) of the random variables $\boldsymbol{X}$.

The FORM is used for calculating the structural reliability. In the method, the random variable vector $\boldsymbol{X}$ is firstly transformed to $\boldsymbol{Y}$, the vector of equivalent uncorrelated standard normal variables.[27–29] The component reliability index is computed as $\beta = (\boldsymbol{y}^{*\mathrm{T}}, \ \boldsymbol{y}^*)^{1/2}$ in which $\boldsymbol{y}^* = [y_1 \ \ y_2]$ is the point in the limit state $G(y) = 0$ at a minimum distance from the origin and is referred to the most probable point (MPP) to failure. A geometrical illustration for a limit state involving two random variables, y_1 and y_2, is shown in Fig. 1. The failure probability is approximated by

$$P(G \geqslant 0) = \Phi(\beta) \quad (4)$$

where Φ is the cumulative distribution function of the standard normal variable.

The MPP can be found by either an iterative calculation or solving a minimization problem:

$$\boldsymbol{y}_{i+1} = [\boldsymbol{y}_i^{\mathrm{T}}\alpha_i - G(\boldsymbol{y}_i)/|\nabla G(\boldsymbol{y}_i)|]\boldsymbol{\alpha}_i \quad (5)$$

$$\min_{\boldsymbol{y}} \|\boldsymbol{y}\|$$
$$\text{s.t.} \quad G(\boldsymbol{y}) = 0 \quad (6)$$

where $\nabla G(\boldsymbol{y}_i)$ is the gradient vector of the limit state function at $\boldsymbol{y}_i$, and $\boldsymbol{\alpha}_i$ the unit vector normal to the limit state surface away from the origin.

2.3. PSO

PSO which is an evolutionary global algorithm has gained popularity recently.[17,18] Similar to other existing EAs, PSO is a population-based optimization method. Distinct from other EAs where knowledge is destroyed between generations, individuals in the population of PSO retain memory of known good solutions as the search for better solutions continues. Hence, PSO has higher speed of convergence than other evolutionary search algorithms. The other advantage of PSO is that it's easy to implement and there are fewer parameters to adjust. The velocity vector of each particle is calculated according to the formula:

$$\boldsymbol{v}_k^i = w\boldsymbol{v}_{k-1}^i + c_1 r_1(\boldsymbol{p}_{k-1}^i - \boldsymbol{x}_{k-1}^i) + c_2 r_2(\boldsymbol{p}_{k-1}^{g} - \boldsymbol{x}_{k-1}^i) \tag{7}$$

where the superscript i denotes the particle and the subscript k the iteration number; $\boldsymbol{v}$ denotes the velocity and $\boldsymbol{x}$ the position; r_1 and r_2 are uniformly distributed random numbers in the interval $[0, 1]$; c_1 and c_2 are the acceleration constants; w is the inertia weight; $\boldsymbol{p}_{k-1}^i$ is the best position of particle i and $\boldsymbol{p}_{k-1}^{g}$ the global best position attained by the swarm at iteration $k-1$. The position of each particle at iteration k is calculated using the formula:

$$\boldsymbol{x}_k^i = \boldsymbol{x}_{k-1}^i + \boldsymbol{v}_k^i \tag{8}$$

2.4. Procedure for the reliability-based optimum design of structures

The optimization procedure for the reliability-based optimum design can be described in Fig. 2. The approach includes three modules: (1) stress analysis by ANSYS; (2) reliability calculation; and (3) optimization. Apart from ANSYS, the procedure is essentially written in the compute software MATLAB.

Firstly, the particles are initialized with random position values and random velocities. Secondly, ANSYS is called at background to calculate the stress of the structure, and outputs these data to an external file. Thirdly, MATLAB reads the file and calculates the system reliability. The optimization algorithm evaluates fitness of each swarm and then accounts the best previous experience and the best experience of all other members of the swarm at current iteration. Each swarm updates itself through the best solutions mentioned above. The updated swarms are returned to ANSYS for the next iteration. This process is repeated until the number of iteration reaches the pre-determined maximum iteration number. The data from ANSYS and MATLAB are exchanged, back and forth, with each other in the whole optimization process.

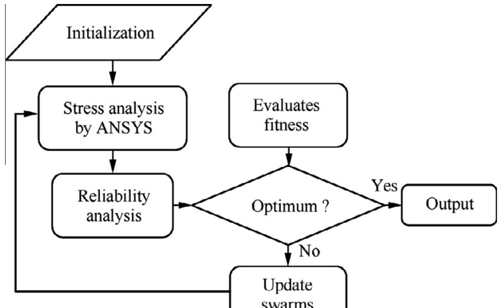

Fig. 2 Procedure for the reliability-based optimum design.

3. Reliability-based design of fiber reinforced plastics (FRP) laminates and composite cylindrical shells

3.1. Optimization design of an FRP laminate and the convergence validation of PSO–FEA procedure

When FRP laminated plates are used in aerospace structures, the primary concern to designers is how to reduce their weight without compromising their performance. Such issues can usually be summarized as follows: minimize the structural weight with reliability constraints. The design model can be formulated as

$$\begin{aligned} &\min_{\boldsymbol{d}} \quad h(\boldsymbol{d}) = \sum_{i=1}^{n} h_i(\boldsymbol{d}) \\ &\text{s.t.} \quad P\{g \geqslant 0\} = \Phi(\beta) \geqslant R_{\mathrm{t}} \end{aligned} \tag{9}$$

where $\boldsymbol{d}$ is the design variable (e.g., ply angle, etc.), $h(\boldsymbol{d})$ the total ply thickness, $\Phi(\beta)$ the system reliability, and R_{t} the target system reliability.

Consider a simply supported symmetric laminated composite plate (20 cm × 12.5 cm) under both compression load N_x = 500 kN·m and uniform transverse load p = 0.2 MPa, as shown in Fig. 3.

The stacking structure is $[0/+45/-45/90]^{\mathrm{s}}$. The thicknesses of 0° layer and 90° layer are both 0.25 mm, and those of ±45° layer and −45° layer are $h_1 \times 0.125$ mm, $h_2 \times 0.125$ mm, respectively. The laminate is made of T300/5208 graphite/epoxy material with E_1 = 181 GPa, E_2 = 10.3 GPa, G_{12} = 7.17 GPa, and μ_{12} = 0.28. The strength parameters are considered as normally distributed random variables of independence and their distribution characteristics are shown in Table 1. The objective function of this problem is $f = h_1 + h_2$ with h_1 and h_2 being the design variables. The target system reliability is R_{t} = 0.99.

The proposed method combining PSO and ANSYS is used in the reliability-based optimum design calculation. The population size and the maximum iteration are 20 and 40, respectively. The results are listed in Table 2. Since performing finite element analysis for composite structure is a time-consuming process, the computational cost required by the reliability calculation and optimization is negligibly low, as compared to that by finite element analysis. Thus, approximately, the efficiency of the two methods is compared by the number of finite element analyses (N_{FEA}). It is observed that the method combining PSO and ANSYS obtains a better solution than that obtained by the optimum toolbox of ANSYS.

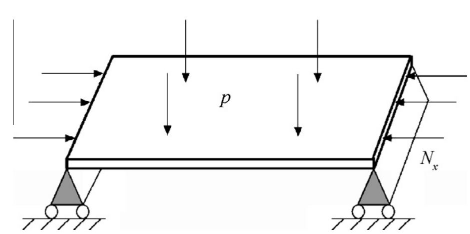

Fig. 3 A laminate subjected to axial compression load and uniform lateral load.

Table 1 Random variables.

Distribution	X_T (MPa)	X_C (MPa)	Y_T (MPa)	Y_C (MPa)	S (MPa)
Mean	1500	1500	48	246	68
Standard deviation	150	150	4.8	24.6	6.8

Table 2 Reliability-based design results.

Method	Initial solution		Optimal solution		f (10^{-4}m)	$\Phi(\beta)$	N_{FEA}
PSO-ANSYS	Random		5.013	4.711	9.724	0.990	800
ANSYS	2.000	2.000	6.813	7.039	13.852	0.998	626
	4.000	4.000	5.116	4.952	10.069	0.992	511
	6.000	6.000	5.235	5.018	10.253	0.993	478
	8.000	8.000	6.478	6.320	12.798	0.996	557

Meanwhile, the proposed procedure can reach the global optimum regardless of randomly generated initial candidate solutions (population). The quality of the optimal solution of the optimum toolbox of ANSYS which is based on the gradient optimization theory and function approximation, however, depends on the selection of an initial solution: a better initial solution leads to a better optimal solution, and a worse one reduces the quality of the optimal solution. However, the initial solution in the PSO–ANSYS procedure is randomly generated, and the quality of the optimal solution has nothing to do with the selection of the initial solution. Due to employment of the function approximations, the computational cost required by the optimum toolbox of ANSYS is less than that by the proposed method as shown in Table 2. Thus, our next work will focus on improving the efficiency of the proposed method.

3.2. Optimization design of a fiber-reinforced composite cylindrical skirt

Consider a fiber-reinforced composite cylindrical skirt for solid rocket cases as shown in Fig. 4,[30] in which h_θ and h_c stand for the thicknesses of the inner (angle-ply layer) and outer (cross-ply layer) region. Its length $L = 0.5$ m, radius $R = 0.3$ m (from the center to the mid-surface of the composite layers), and total thickness h is considered as the objective. Let the mid-surface of the cylindrical shell of the skirt be the reference surface, and let the origin of the coordinates be located at one end of the cylinder. The fiber orientations are symmetric with respect to the mid-surface of the cylindrical shell. The orthogonal coordinates x, y, and z are measured in the longitudinal, circumferential, and radial directions, respectively. The shell has a symmetric and balanced composite structure with a stacking sequence $[90/0/+\theta/-\theta]_s$. θ is the angle between the fiber direction and the longitudinal axis. The composite cylindrical skirt with simply supported boundary conditions

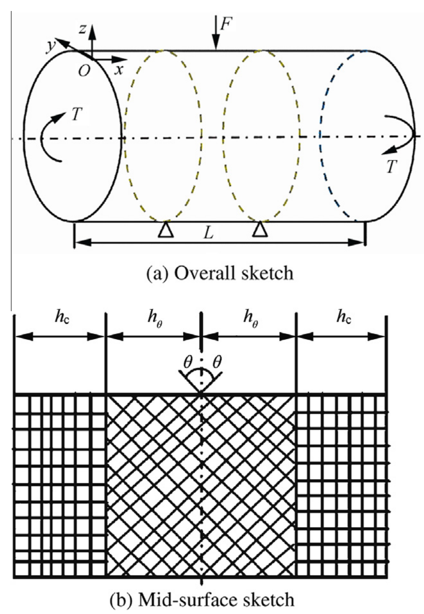

Fig. 4 A fiber-reinforced composite cylindrical shell.

($w = v = 0$ at $x = L/5$, $4L/5$) is subjected to torque T at the ends and a concentrated force F at the middle.

The material properties are given as $E_x = 137$ GPa, $E_y = 8.17$ GPa, $G_{xy} = 4.75$ GPa, and $\nu_{xy} = 0.316$. The strength parameters are normally distributed random variables (see Table 3).

The design objective is to determine the thicknesses h_θ, h_c and the angle θ, to minimize the total weight or equivalently, the total thickness of the shell under the probabilistic constraint $R \geqslant 0.9938$. The constraint condition is equivalent to:

Table 3 Statistical properties of strength parameters.

Distribution	X_T (MPa)	X_C (MPa)	Y_T (MPa)	Y_C (MPa)	S (MPa)
Mean	1470	980	39.2	78.4	78.4
Standard deviation	147	98	3.92	7.84	78.4

Table 4 Optimal design results under different values of F.

F (kN)	T (kN·m)	h_θ (mm)	h_c (mm)	θ (°)	f (mm)	β
10	70	5.06	4.08	33.71	9.14	2.501
20	70	8.17	5.16	38.08	13.33	2.502
50	70	13.17	8.96	35.22	22.13	2.501
70	70	16.72	9.28	34.48	26.00	2.501

reliability index $\beta \geqslant 2.5$. The optimization design problem can be modeled as

$$\begin{aligned} &\text{Find} \quad h_\theta,\ h_c,\ \theta \\ &\text{Min} \quad f(h) = h_\theta + h_c \\ &\text{s.t.} \quad P(g \geqslant 0) \geqslant 0.9938 \text{ or } \beta \geqslant 2.5 \\ &\qquad 0 \leqslant h_\theta \leqslant R/10,\ 0 \leqslant h_c \leqslant R/10 \\ &\qquad 0 \leqslant h_c + h_\theta \leqslant R/10, \quad 0^\circ \leqslant \theta \leqslant 90^\circ \end{aligned} \tag{10}$$

The proposed method combining PSO and ANSYS is adopted in the optimum design. The optimal results for the composite cylindrical shell under different combinations of concentrated force F and fixed torque T are listed in Table 4. As F increases, both the cross-ply and angle-ply layer thickness increase. But the latter (inner layer) is always thicker than the former (outer layer). The optimal fiber angles vary in a small range (33–38°).

Table 5 shows the optimal design results for a shell with $[\theta/-\theta/90/0]_s$. As compared with Table 4, similar features are observed, i.e., the cross-ply layer (inner layer) is thicker than the angle-ply one (outer layer) except for F = 20 kN. The optimal fiber angles are greater than those for $[90/0/+\theta/-\theta]_s$. The total thickness displays a similar change tendency as in Table 4.

For every load condition, the total thickness is greater than that of $[90/0/+\theta/-\theta]_s$, indicating that $[90/0/+\theta/-\theta]_s$ is better than $[\theta/-\theta/90/0]_s$ for the loading conditions.

4. Reliability-based design optimization of a composite pressure vessel

4.1. Conventional strength design for composite pressure vessels

Filament-wound structures such as pressure vessels, pipes and motor cases of rockets are wildly used in aerospace applications.[31,32] In this section, the reliability-based optimal design of a composite pressure vessel is investigated.

A composite pressure vessel is composed of a cylindrical part and a head part. In the cylindrical region, there are inner helical composite layers and outer circular layers. The outer circular layers are assigned at a fixed fiber angle ($\theta \approx$ 80–90°) and a certain thickness t_θ. If the wrap angle of the helical layer in the cylindrical part is α_0 and the corresponding thickness is t_0, then the fiber angle and thickness in the head part are determined according to following relations[29]:

$$\begin{cases} \sin\alpha = \dfrac{R}{x}\sin\alpha_0 \\ t_\alpha = \dfrac{R}{x}\cdot\dfrac{\cos\alpha_0}{\cos\alpha}t_0 \end{cases} \tag{11}$$

where R, α_0, t_0 are the radius, fiber angle, and thickness of the helical layer in the cylindrical region, while x, α, t_α are the radius, fiber angle, and thickness of any point at the head shape.

In the conventional strength design for composite pressure vessels, only strength of the cylindrical part is considered. The design results based on the equi-strength criterion are

$$\begin{cases} t_0 = \dfrac{pR}{2[\sigma]\cos^2\alpha_0} \\ t_\theta = \dfrac{3pR}{2[\sigma]} - t_0 \end{cases} \tag{12}$$

where $[\sigma]$ denotes the allowable stress in the fiber direction.

Consider a composite pressure vessel under internal pressure loads p. The cylindrical region of the vessel is composed of an inner helical layer and an outer circular layer. The geometry of the vessel is shown in Fig. 5. The wrap angle of the helical layer in the cylindrical portion is $\pm\alpha_0$, and the corresponding thickness is h_1. The circular layer thickness is h_2. The fiber angle and thickness in the head part are determined according to Eq. (12). The composite material is T800/Epoxy (Toray). Mechanical properties are listed in Table 6. Table 7 shows the statistical characteristics of the strength parameters. p = 10 MPa, $\alpha_0 = \pm 20^\circ$, $\theta = 90^\circ$, and $[\sigma]$ = 767.7 MPa. The design results are: t_0 = 5.47 mm, t_θ = 3.32 mm.

FE analysis based on ANSYS is conducted for the vessel. Figs. 6 and 7 show the fiber direction stress and the transverse stress in the most inner layer (helical layer). The maximum stresses locate at the transitional part due to stress concentration. The fiber direction stress satisfies the strength condition, i.e., $\sigma_{LL} < [\sigma]$ = 767.7 MPa. The maximum transverse stress is σ_{TT} = 33.39 MPa, which approaches the strength limit (36.4 MPa). Considering the variation of composite strength, it can be concluded that the above design can be taken as a reference but has the risk of failure. Alternative design methods are needed to get more reliable solutions that are described in the following section.

Table 5 Optimal design results for the shell with stacking sequence $[\theta/-\theta/90/0]_s$.

F (kN)	T (kN·m)	h_θ (mm)	h_c (mm)	θ (°)	f (mm)	β
10	70	4.10	6.00	39.11	10.10	2.504
20	70	8.09	6.66	43.60	14.75	2.508
50	70	10.51	13.83	41.42	24.34	2.501
70	70	13.18	16.04	44.71	29.22	2.518

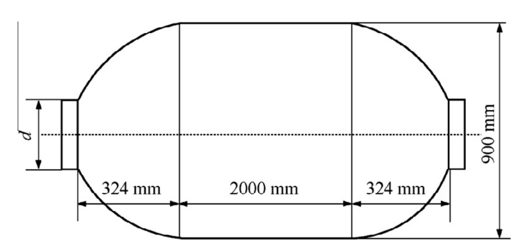

Fig. 5 Geometry of the composite pressure vessel.

Table 6 Material properties of T-800/Epoxy.

E_2 (GPa)	E_2, E_3 (GPa)	G_{12}, G_{13} (GPa)	G_{23} (GPa)	υ_{12}, υ_{13}	υ_{23}
142	3.14	4.69	1.0	0.33	0.45

Table 7 Strength parameters.

Distribution	X_T (MPa)	X_C (MPa)	Y_T, Z_T (MPa)	Y_C, Z_C (MPa)	R, S, T (MPa)
Mean	2687	1441	36.4	70	59.6
Standard deviation	268.7	144.1	3.64	7.0	5.96

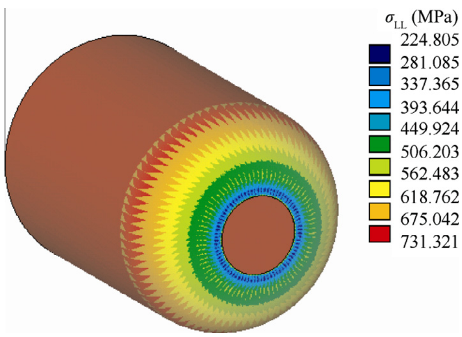

Fig. 6 Direct stress σ_{LL} in the fiber direction in the inner layer.

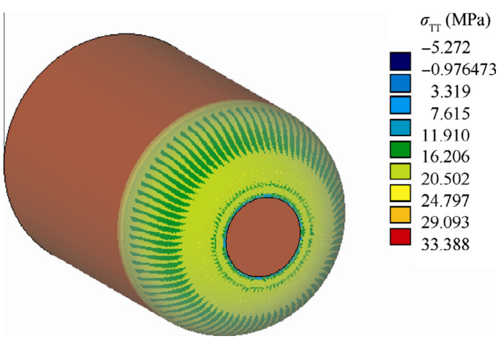

Fig. 7 Direct stress σ_{TT} in the transverse direction in the inner layer.

4.2. Reliability design for composite pressure vessels

To account for the effect of uncertainties in the design of pressure vessels, a reliability design is conducted. In the above example, all the random variables are assumed to be uncorrelated normally distributed variables for the sake of illustration. The optimization problem is expressed as

$$\begin{aligned} &\text{Find} \quad \alpha_0,\ h_1,\ h_2 \\ &\text{Min} \quad H = 2h_1 + h_2 \\ &\text{s.t.} \quad \Phi(\beta_s) \geqslant 0.99, \quad 10 \leqslant \alpha_0 \leqslant 85 \end{aligned} \tag{13}$$

Using the method combining PSO and ANSYS, the optimal laminate structure corresponding to different internal pressure loads are computed and listed in Table 8.

It can be seen that the thickness of the optimum structure increases with the increase of the internal pressure as expected. It is worthy to mention that the wrap angle (α_0) of the helical layer in the cylindrical region also increases as the load increases. This is because that the rate of the circumferential forces increases faster than that of the meridional stress when the internal pressure increases. The helical layer bears not only the meridional stress, but also a part of the circumferential forces. To make the stress distribute more reasonably, the wrap angle (α_0) of the helical layer should increase as the load increases.

Table 8 Optimal solutions under different internal pressures.

P (MPa)	h_1 (mm)	h_2 (mm)	α_0 (°)	H (mm)
5	4.21	2.59	10.13	11.01
10	8.55	2.63	18.18	19.73
15	9.59	4.07	20.58	23.25
20	11.61	5.46	21.80	28.68
30	15.62	7.62	26.55	38.86
40	19.37	10.28	28.06	49.02
50	22.56	11.71	28.93	56.82

5. Conclusions

Owing to the high sensitivity of strength to load conditions and other factors for composite structures, high reliability is usually required for them. The present work concentrates on developing a method for the reliability-based optimum design of composite structures. The method includes three modules: (1) stress analysis; (2) reliability calculation; and (3) optimization. ANSYS is employed to accurately evaluate stresses of complicated composite structures, and PSO is used to find the global solution. Except stress analysis, the proposed method is written in MATLAB. The data from ANSYS and MALTAB are exchanged in each cycle. Several examples are carried out to demonstrate the effectiveness of the proposed method. For the reliability-based design optimization of composite pressure vessels, we get the change law of wrap angle α_0 and layer thickness with the internal pressure load p, which provides the engineering application with very important reference values. Our future work will focus on reducing the computational cost of the method.

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